

*Opinion piece*

# Evolution and evolvability: celebrating Darwin 200

**The concept of ‘evolvability’ is increasingly coming to dominate considerations of evolutionary change. There are, however, a number of different interpretations that have been put on the idea of evolvability, differing in the time scales over which the concept is applied. For some, evolvability characterizes the potential for future adaptive mutation and evolution. Others use evolvability to capture the nature of genetic variation as it exists in populations, particularly in terms of the genetic covariances between traits. In the latter use of the term, the applicability of the idea of evolvability as a measure of population’s capacity to respond to natural selection rests on one, but not the only, view of the way in which we should envisage the process of natural selection. Perhaps the most potentially confusing aspects of the concept of evolvability are seen in the relationship between evolvability and robustness.**

**Keywords:** evolvability; selection; fitness

## 1. INTRODUCTION

The study of evolution in this century has been accompanied increasingly by the consideration of ‘evolvability’. A search of the Web of Science in the years from 2004 to 2008 reveals 402 papers containing evolvability in title, abstract or keywords, compared with 212 in the years from 1999 to 2003 and only 33 in the previous 5 years. What, then, is evolvability, and what is the cause of the sudden interest in this concept? Some of the interest has come from the rise of systems biology, in which the properties of genetic network structures are investigated (Hinze & Adami 2008). In a general sense, evolvability refers to the ability of populations to evolve in an adaptive way. However, as so often with general concepts in biology, different authors have used the idea in different ways. In this piece, I will particularly focus on the dichotomy between two concepts of evolvability. The first defines the evolvability of a population as expressing its prospective ability to produce new mutations that can be used in adaptive evolution in the medium to long term. The second defines the evolvability of a population as a description of its current standing crop of genetic variability, and the consequence of the extent and nature of this variation for the population’s ability to respond to current selective pressures.

## 2. EVOLVABILITY IN THE MEDIUM TO LONG TERM

Adaptive evolution occurs through the sequential introduction into populations of advantageous mutations,

some of which then spread to fixation as a result of their selective effects. This standard population genetic model of evolution envisages the trajectories of evolutionary change being governed by mutation, selection and genetic drift, in a population defined by a species’ demography and geographical structure. The selective changes are driven by the relative fitnesses of genotypes and the alleles that they contain as the fittest alleles spread to fixation in the population.

This population genetic view, in which relative allelic fitness determines outcomes, is so ingrained a view of evolutionary change that it is through this logic that we identify which explanations are evolutionarily legitimate. We say that, if an initially rare mutation conferring a new trait has a higher fitness than its alleles, then such a mutant will (provided it is not lost by drift early on) spread to fixation. For example, rejection of the ‘Good of the Species’ argument for altruistic behaviour typically relies on the argument that the fitness of a genetic variant that no longer performed altruistic acts towards other members of the species, but merely received the benefit of altruistic acts by others, would have a selective advantage and would thus spread (Williams 1966).

In this model it is current fitness, rather than any potential future gain that genotypes may convey to a population, which determines evolutionary outcomes. The ability or inability of the fittest genotypes to subsequently mutate into genotypes that confer further selective advantage is irrelevant. Selection’s lack of foresight, rather, fixes the allele with the highest fitness from those currently available, even if the resulting genotype represents some sort of ‘evolutionary dead end’, with no ability to change in an adaptive way in the future. The spread, when initially rare, of the sickle cell allele at the  $\beta$ -globin locus in man, driven by its advantage when in the heterozygous state, and notwithstanding the fatal disease generated by its homozygosity, illustrates this lack of foresight (Allison 1954). If evolvability represents the long-term evolutionary potential of a population, there is no reason why individual selection will necessarily maximize it. On the contrary, logically, individual selection could have the effect of destroying evolvability.

## 3. IS THE CONTINUING MAINTENANCE OF EVOLVABILITY A PARADOX AND IF NOT, WHY NOT?

Thus, one can imagine that fixation of the fittest genotype from those presently available might have detrimental effects on the population’s evolvability—its ability to adapt in the future. But is this a real problem for our understanding of evolution? Two types of explanations might potentially account for the persistence of this kind of evolvability. The first is the possibility that fixation of the fittest allele from those currently available will, in reality, tend to increase evolvability, rather than destroying it. The second is that selection, or its equivalent, may operate at levels higher than individual fitness, and that group or species selection may maintain evolvability in the long run.

#### 4. INDIVIDUAL FITNESS

The key to our understanding of the way in which genetic changes in a species affect the capacity for subsequent adaptive change is the relationship between genotype, environment and the distribution of fitness effects of new mutations. Some (Fisher 1930; Orr 1998) have suggested that the distribution of fitness effects of advantageous mutations can be predicted on theoretical grounds, but surely the specific biology of the species and its interaction with its environment must be the main determinant of such a distribution. We have to think only of insecticide resistance mutations to identify an extreme case of such a phenomenon. The crucial issue is the impact of adaptive substitutions on the ability of the population to make further adaptive changes in subsequent environmental challenges. For Kirshner & Gerhart (1998), the developmental process, in animals in particular, is such as to enhance the probability that new mutations changing phenotype will be adaptive, and the adaptive substitutions occurring serve to reinforce the ability of the developmental process to subsequently change adaptively. Draghi & Wagner (2007) have argued on theoretical grounds that adaptive substitutions will tend to increase future adaptability. This has also been suggested by others in the context of evolution of the primary sequence of proteins (Earl & Deem 2004). Colegrave & Collins (2008) make the point that experimental evolution allows us to assess these issues empirically, along with the impacts on evolvability of more simple changes such as an elevation in the overall mutation rate.

#### 5. SELECTION AT 'HIGHER LEVELS'

Many interpret the evolutionary success of whole groups of organisms, such as the vertebrates, as being the consequence of specific changes in their ancestors, no doubt driven by individual selection, but which subsequently had the effect of promoting diversification and evolutionary success, by enhancing speciation and minimizing extinction rates. Examined in this light, the evolutionary explanation of a phenotypic trait requires not merely a demonstration that fixation of the trait would follow in what was an initially polymorphic population, but also a demonstration that the continued existence of the species itself would not be threatened by the fixation process being imagined. It is, after all, straightforward to imagine behaviours, such as spiteful intraspecific interactions, which could increase the chance of species extinction, notwithstanding their ability to spread by natural selection, and spiteful interactions have indeed been documented (Gardner *et al.* 2004). It could be that individual species show a tendency to evolve towards an inability to respond adaptively to subsequent environmental changes—at the level of individual selection, non-evolvability could, in principle, be favoured. However, if the ability of lineages to avoid extinction varied between lineages, with those remaining evolvable having lower probabilities of extinction, evolvability could be stably maintained in many lineages through selection at the level of species.

#### 6. EVOLVABILITY TO REPRESENT THE GENETIC VARIATION IN SPECIFIC POPULATION

The other main concept for which evolvability has been used is a description of the genetic variability in a population. This idea is connected to the ability of populations to respond to artificial selection for specific traits, where the response to selection is proportional to the narrow sense heritability,  $h^2$ . Analogously, were natural selection to operate on a specific trait or suite of traits, then populations would or would not respond to this selection by changing their mean values of the trait or traits. In the context of wild populations, Houle (1992) noted that the observed low heritability of fitness-related traits might be deceptive, since these traits have high environmental standard deviations relative to their means. He suggested that the additive genetic coefficient of variation in a trait is a better predictor than is the heritability of a population's ability to respond to selection, and thus can be viewed as a measure of evolvability. Also important, however, are the genetic covariances between traits. Lande and co-workers (Lande 1979; Lande & Arnold 1983) demonstrated that the response to selection depends not only on the selection imposed and the narrow sense heritability, but also on the genetic variance and covariance matrix  $\mathbf{G}$ . Schluter (1996) suggested that the first principal component of the  $\mathbf{G}$  matrix can be seen as a prediction of the most likely outcome of multivariate selection, and this was therefore defined as the direction of maximum evolvability. Hansen & Houle (2008) develop this concept in a more explicit and quantitative way, in their 'conditional evolvability', to identify from the  $\mathbf{G}$  matrix the likely outcomes of directional selection.

Discussion of the ability of populations to respond to natural selection raises important conceptual issues about the relationship between natural selection and the concept of fitness. One view regards natural selection, analogous to the selection that is exercised by a plant or animal breeder, as an external force that 'acts' on the phenotypic variation that exists in the population. Another view (Brookfield 2002) is that fitness is the average of the product of viability and fertility for a genotypic class. This approach sees fitness as a phenotype, albeit an environment-dependent one, rather than a secondary phenomenon caused by the combination of a particular phenotype and an actively selective environment. Selection, in this approach, is simply a difference in fitnesses. This view of fitness is more helpful in the consideration of unconditional lethal mutations, for example, where death is not the result of any specific environmental factor but rather the invariable phenotype associated with a particular genotype. A fitness-centred view of natural selection creates interesting questions when issues of evolvability are considered. Specifically, one can imagine a hypothetical, and unrealistic, population in which there are multiple traits showing strong and significant selection gradients, but where negative genetic covariances have the result that all genotypes have equal fitnesses. How should we view such a population? It could be seen as a population undergoing natural selection for multiple traits, but with zero evolvability. Alternatively, a fitness-centred view would say that since there is no variance for fitness there is no selection, and thus it is an absence

of selection, not an absence of evolvability, which prevents evolutionary change.

Another danger in seeing selection as an external force that acts on the phenotype in a way analogous to artificial selection is that this may mislead us into a thinking that when a correlation between a phenotypic trait and measures of individual fitness is seen, this necessarily implies that the trait values cause the fitness differences. Theoretically, it is quite possible for the phenotypic values of a trait to be correlated with measures of individual fitness without the genotypic values for the trait being correlated in a similar way. This is illustrated by the study of Kruuk *et al.* (2002). Antler size in red deer *Cervus elaphus* was shown to be positively correlated with male lifetime breeding success, suggesting a selective gradient. While narrow sense heritability of antler mass was estimated to be over 30 per cent, there was no detectable response to selection, in contradiction with the breeders' equation where the response to selection should have been equal to the selection differential multiplied by the heritability. One possible explanation of this observation is that there is an environmentally induced covariance between the trait and measured fitness. Under this model, their nutritional state has caused some males to have large antlers and high measured fitness relative to the means. These males measured as having high fitness have genotypic values for antler size that are equal to the population mean, and thus there is no response to the apparent selection.

## 7. ROBUSTNESS AND EVOLVABILITY

Many have investigated the link between 'evolvability' and 'robustness' (Wagner 2005). There are two contradictory ways of viewing robustness. One view sees robustness as the ability of the organism to change by mutation to create a new phenotype that is viable and fertile, and which might, in some environments, be of a higher fitness than the pre-existing genotype (Kirshner & Gerhart 1998). In this case, robustness refers to an ability to make potentially adaptive phenotypic changes. However, another vision of robustness is that, just as an organism can be robust to environmental change, being able to make the same phenotype in differing environments, so organisms may be genetically robust in the sense of making a fixed, adaptive, phenotype despite having undergone mutation. This latter meaning of robustness overlaps with the concept of genetic redundancy. Clearly, these differing ideas of robustness are intimately connected to the concepts of evolvability. A robustness defined as the ability to make viable changes in the phenotype will be positively correlated with evolvability. However, a robustness expressing the ability to undergo mutation without phenotypic change would be expected, at face value, to show a negative correlation with evolvability. However, in the reality of the actual molecular biological situation, in which, frequently, robustness to mutation is the result of redundancy arising from recent gene duplications, these same gene duplications may offer the possibility of more adaptive changes through gain-of-function mutations causing neo-functionalization of redundant copies.

## 8. CONCLUSION

It is probably too early to say whether the concept of evolvability will prove to be useful in the long run, and whether the current excitement will persist. However, there is clearly a danger that, as with 'canalization' in the past, confusion will result as authors use the same word with different meanings and scientific biological debates are rendered fruitless by underlying semantic misunderstandings.

John F.Y. Brookfield\*

*School of Biology, Institute of Genetics, Queens Medical Centre, University of Nottingham, Nottingham NG7 2UH, UK*

\*john.brookfield@nottingham.ac.uk

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